Method and Apparatus for Narrow-Band Disturbance Signal Reduction in Servo Positioning Signals

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Related Application

Priority is claimed from U.S. Provisional Application No. 60/394,854, entitled "Narrow-Band NRRO Reduction Using a Non-linear Filter", filed on July 10, 2002, which is incorporated herein by reference.

Field of the Invention

The present invention relates to reducing positioning errors due to random disturbances in servomechanisms and, in particular, to reducing non-repeatable run out (NRRO) due to narrow-band disturbance signals in disk drive servo systems.

Background of the Invention

Background for the present invention is provided herein in connection with a disk drive servo system. It

should be noted, however, that the present invention is not intended to be limited to such systems.

A disk drive is a data storage device that stores servo and user data in substantially concentric tracks on a data storage disk. During disk drive operation, the data storage disk is rotated about an axis while a transducer is used to read data from and/or write data to a target track of the disk. A servo control loop is used to position the transducer above the target track while the data transfer is taking place. The servo control loop uses servo data read from a surface of the data storage disk as position feedback to maintain the transducer in a substantially centered position above the target track that is dictated by the mechanical properties of the disk drive.

Typically, servo data includes magnetic flux transitions, such that when the transducer passes over the flux transitions, the transducer generates a read-back signal. The read-back signal can be demodulated and decoded to provide a position error signal (PES) that indicates position of the transducer relative to a track. The PES signal is utilized to generate an input signal for

the head positioning servo-loop to correct the position of the transducer relative to the track, as necessary.

However, certain type of disturbances in the disk drive can increase positioning errors. Such disturbances can have a variable amplitude at a very narrow frequency band. An example random disturbance can be non-repeatable run out (NRRO) due to disk rocking mode, which is excited by imperfections of balls in the disk drive spindle motor bearing. The range of the disturbance amplitude varies from disk drive to disk drive and from time to time.

Therefore, attempts have been made to attenuate a portion of PES signals that are due to disturbances such as NRRO. In one conventional approach, a notch filter is adopted to attenuate narrow-band disturbance signals in the PES. In order to provide adequate attenuation, the notch filter has a sharp and deep decrease in gain around the frequency of the disturbance. The amount of notch is determined empirically. However, this approach has a number of drawbacks. First, there is always a fixed level of attenuation regardless of the disturbance level, which can vary significantly. Further, the disturbance may not occur in all disk drives, and not all the time. For

example, there may be more disturbance due to temperature rise, or due to other excitation effect/force. A conventional, linear disturbance signal-attenuator, which uses a notch filter, attenuates the disturbance signal even if there is no, or minimal, disturbance. This increases position error and lowers performance.

Further, using a notch filter affects the error transfer function on the entire frequency range. (The error transfer function is the frequency response that determines the position error.) Because the resulting error transfer function is distorted by the notch filter from its highly optimized original shape, the performance is worse if the targeted disturbance is not present in the PES. Additionally, the fixed (linear) notch filter causes "ringing" problems in the steady-state response due to the exaggerated frequency response at the notch frequency.

As a compromise, in some conventional servo controllers, a notch filter with very weak attenuation, around 3dB, is utilized. However, weak attenuation is not sufficient when the disturbance is large. Using a notch filter for attenuating disturbances is further complicated because the notch frequency can fall on a phase cross-over

frequency, where robustness constraints severely limit notch design.

Another conventional approach involves use of a state estimator that utilizes an internal model principle to estimate the disturbance in a torque disturbance form. The estimator is based on Kalman filter theory, requiring that statistical characteristics be known *a priori* to design the filter. As this is also a linear system, it suffers from similar problems mentioned in relation to the notch filter. Such a linear system deteriorates the performance of the servo controller, if the target disturbance is very small or not present.

Accordingly, there is a need for a method and apparatus to reduce the positioning error in the PES due to the narrow-band disturbances that introduce a disturbance signal in the PES, while maintaining the performance of the servo controller in terms of positioning performance and settling after seek.

Brief Summary of the Invention

The present invention addresses the above needs. In one embodiment, the present invention provides a method for

operating a servo system that includes a first member and a second member that is positionable relative to the first member in response to position signals. A position signal is generated to cause the second member to be positioned to a desired location relative to the first member. Disturbances in the servo-system introduce disturbance signals into the position signal. According to an embodiment of the present invention, positioning errors due to such disturbances are reduced by non-linear attenuation. In one example, this includes the steps of selectively varying a disturbance signal in the position signal as a function of the magnitude of the disturbance signal. As such, the level of the disturbance signal varies as a non-linear function of the magnitude of the disturbance signal.

Another embodiment of the above method includes the steps of: filtering the position signal to selectively pass the disturbance signal; generating a correction signal having a magnitude that varies as a non-linear function of the magnitude of the disturbance signal; and combining the correction signal with the position signal to generate a corrected position signal for a position controller, enabling the position controller to selectively react to the disturbance with varying amplitude.

The step of filtering the position signal may further comprise the steps of: determining the frequency band of the disturbance signal and filtering the position signal using a peak filter to selectively pass the disturbance signal. In another case, the step of filtering the position signal includes the steps of determining the frequency band and magnitude range of the disturbance signal, and filtering the position signal using a peak filter based on the frequency band and magnitude range of the disturbance signal to selectively pass the disturbance signal.

In an example implementation of the above method, the present invention provides a servo system having a control loop including: a servo controller that generates a position signal coupled to said second member causing said second member to be positioned to a desired location relative to said first member; and an attenuator that selectively reduces positioning errors due to disturbances by non-linear attenuation.

As noted, disturbances in the servo-system introduce disturbance signals into the position signal. The

attenuator includes a gain controller that selectively varies (e.g., amplifies or attenuates) a disturbance signal in the position signal, as a non-linear function of the magnitude of the disturbance signal. In one example, the gain controller provides varying amplification/attenuation of the disturbance signal such that reduction of positioning errors increases as a non-linear function of the magnitude of the disturbance signal.

In another version, the attenuator includes: a filter that filters the position signal to selectively pass the disturbance signal; a gain controller that generates a correction signal having a magnitude that varies as a non-linear function of the magnitude of the disturbance signal; and a combiner that combines the correction signal with the position signal to generate a corrected position signal for a position controller, enabling the position controller to selectively react to disturbances having varying amplitudes. The filter comprises a peak filter selected based on the frequency band of the disturbance signal.

In yet another version of the servo system, the position signal includes multiple peaks at different frequencies, and the attenuator includes: a first filter

that filters the position signal to selectively pass a disturbance signal at a first peak frequency; a first gain controller that generates a first correction signal having a magnitude that varies as a non-linear function of the magnitude of said disturbance signal at the first peak frequency; a second filter that filters the position signal to selectively pass a disturbance signal at a second peak frequency; a second gain controller that generates a second correction signal having a magnitude that varies as a non-linear function of the magnitude of said disturbance signal at the second peak frequency; and a combiner that combines the first and/or the second correction signals with the position signal to generate a corrected position signal with selectively varied disturbance signals in a non-linear manner.

Each attenuator can further comprise: a saturation controller that controls the output of the filter to preserve servo-loop stability as the gain controller output increases above a threshold, and a deadzone controller that controls the output of the filter to maintain improved performance of the position controller if the amplitude of the disturbance is below a threshold.

Other objects, embodiments, features and advantages of the invention will be apparent from the following specification taken in conjunction with the following drawings.

Brief Description of the Drawings

Figure 1 shows an example block diagram of certain functional components of an embodiment of a disk drive implementing aspects of the present invention;

Figure 2 shows an example functional arrangement of non-linear filtering of narrow-band disturbance signals in the positioning signal (PES) of the disk drive of **Figure 1**, according to an embodiment of the present invention;

Figures 3A-B show magnitude and phase plots, respectively, of the frequency response of an example peak filter in the arrangement of **Figure 2**;

Figure 4 shows a decomposition plot for PES including a disturbance signal due to rocking mode;

Figure 5 shows the PES plot of **Figure 4**, wherein the disturbance signal due to rocking mode has been attenuated by the arrangement in **Figure 2**;

Figure 6 shows an example functional arrangement of non-linear filtering for attenuating narrow-band disturbance signals in the disk drive of **Figure 1**,

according to another embodiment of the present invention; and

Figure 7 shows an example functional block diagram of a non-linear filtering bank according to yet another embodiment of the present invention.

Detailed Description of the Invention

While this invention is susceptible of embodiments in many different forms, they are shown in the drawings and will herein be described in detail, preferred embodiments of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspects of the invention to the embodiments illustrated. Further, although example embodiments of the present invention are described in connection with a disk drive servo system, it should be noted that the present invention is not intended to be limited to disk drive systems.

Figure 1 illustrates an example disk drive system 100 implementing aspects of the present invention. The disk drive system 100 is operative for performing data storage and retrieval functions for an external host computer 102.

The disk drive system 100 includes: a data storage disk 104, a transducer 106, an actuator assembly 108, a voice coil motor (VCM) 110, a read/write channel 112, an encoder/decoder (ENDEC) 114, an error correction coding (ECC) unit 116, a data buffer memory 118, an interface unit 120, a servo controller 122, and a disk controller/microprocessor 124.

In general, the disk 104 includes one or two disk surfaces (not shown) which are coated with a magnetic material that is capable of changing its magnetic orientation in response to an applied magnetic field. Data is stored digitally in the form of magnetic polarity transitions (frequently referred to as pulses in cells) within concentric tracks on one or more of the disk surfaces. The disk 104 is rotated at a substantially constant spin rate by a spindle motor (not shown) that is speed-controlled by a closed-loop feedback system. Instead of the single disk 104 shown in **Figure 1**, the system 100 can include a plurality of disks all mounted on a single spindle and each serviced by one or more separate transducers.

The transducer 106 is a device that transfers information from/to the disk 104 during read and write operations. The transducer 106 is positioned over the disk 104, typically, by a rotary actuator assembly 108 that pivots about an axis under the power of the VCM 110. During a write operation, a polarity-switchable write current is delivered to the transducer 106 from the read/write channel 112 to induce magnetic polarity transitions onto a desired track of the disk 104. During a read operation, the transducer 106 senses magnetic polarity transitions on a desired track of the disk 104 to create an analog read signal that is indicative of the data stored thereon. Commonly, the transducer 106 is a dual element head having a magneto-resistive read element and an inductive write element.

The VCM 110 receives movement commands from the servo controller 122 for properly positioning the transducer 106 above a desired track of the disk 104 during read and write operations. The servo controller 122 is part of a feedback loop that uses servo information from the surface of the disk 104 to control the movement of the transducer 106 and the actuator assembly 108 in response to commands from the

controller/microprocessor 124. A function of the servo controller is to minimize tracking errors.

During a read operation, the channel 112 receives the analog read-back signal from the transducer 106 and processes the signal to create a digital read signal representative of the data stored on the disk 104. Typically, detection circuitry is included in the channel 112. The channel 112 may also include means for deriving timing information, such as a read clock, from the analog signal.

The disk controller/microprocessor 124 is operative for controlling the operation and timing of the other elements of the system 100. In addition, the controller/microprocessor 124 may perform the functions of some of the elements of the system. For example, the controller/microprocessor 124 may perform some computation functions for the servo controller 122.

Positioning servo bursts on the disk 104 induce analog signals in the transducer 106 that are processed through the channel 112. The channel 112 includes an analog to digital converter (ADC) to convert the analog servo burst

signals to digital values representing the amplitudes of analog signals. The servo controller 122 further processes the digital data to determine transducer position information and provide servo control signals to the VCM 110 for seeking and tracking operations. As such, a servo-loop system is formed such that the VCM 110 moves the actuator assembly 108 and transducer 106 in response to said control input signals.

In one example, servo burst information is read by the transducer 106 from the disk 104. The servo controller 122 and/or the disk controller 124 provide demodulation for processing the digital servo data from the channel 112, and generate transducer/head position information including a position error signal (PES). The servo controller 122 provides control signals to the VCM 110 for positioning the transducer 106 (e.g., seeking to a target track, tracking over a target track, etc.).

After a seek operation to a target track, servo data is used by the servo-loop for maintaining the position of the transducer relative to that track. The PES signal is utilized to generate an input signal for the head

positioning servo-loop to correct the position of the transducer relative to the track as necessary.

As noted, disturbances in the servo-system introduce disturbance signals into the position signal. According to an embodiment of the present invention, the servo controller 122 implements a method for attenuating positioning errors due to narrow-band disturbances in the disk drive position signal (e.g., PES). **Figure 2** shows an example functional block diagram of an embodiment of a non-linear filtering arrangement 200 in the servo controller 122, according to the present invention, for attenuating positioning errors due to narrow-band disturbances in the PES. The example nonlinear filtering arrangement 200 in **Figure 2** includes a band pass filter function 202 and a non-linear gain function 204. The filter 202 filters the PES and passes the disturbance signal in the PES, to the gain function 204 for selective non-linear variation, wherein the output of the gain function 204 is a correction signal that is combined with the original PES signal in a combiner node 206 to generate a corrected PES signal.

In this example, the output of the gain function 204 is a non-linear value and the combiner node 206 is a

summing node. The variable gain of the non-linear function 204 adjusts the level of position error attenuation in accordance with the strength of the disturbance causing the position error. The description below is provided in the context that the arrangement in **Figure 2** attenuates non-repeatable run out (NRRO) position errors in the PES.

In this example, the band pass filter 202 comprises a peak filter designed to pass a selected narrow-band frequency component of the PES only, wherein the narrow-band frequency includes the disturbance signal to be attenuated.

The filter 202 comprises a peak filter, and the frequency response of the peak filter 202 is selected based on the frequency range of the disturbance signal to be processed. In one example, the peak filter frequency can be determined by examining the frequency of the target disturbance. **Figures 3A-B** show magnitude plot 208 and phase plot 210, respectively, of the frequency response of an example peak filter 202. This example peak filter 202 is designed for NRRO disturbance signals with the peak of about 2.5 on the linear scale, and frequency location/range at about 1.9 KHz.

Referring back to **Figure 2**, after the PES is filtered by the peak filter 202, the non-linear gain function 204 performs arithmetic operations on the filtered PES to output correction values to be combined with the PES. In one embodiment, the nonlinear gain function 204 comprises an odd function *f(u)* wherein the product of input and output are always positive. The output values of the gain function 204 are added to the original PES signal by the summing node 206 in the arrangement 200 of **Figure 2** to attenuate the position error due to said disturbances, in the PES.

An example non-linear gain function *f(u)* is a cubic gain function, having two tunable parameters *M*, *N*, according to relation (1) below:

$$f(u) = M\left(\frac{u}{N}\right)^3 \qquad (1)$$

The parameters *M*, *N* can be selected to signify the effect of the cubic function *f(u)* only when there is a strong distrubance at the target disturbance frequency. The value of *N* is selected based on the level/magnitude of NRRO disturbance signal (i.e., *u*), so that if the disturbance signal is smaller than *N*, then the ratio *u/N* is

reduced when cubed, but if the disturbance signal is greater than N then the ratio u/N is increased when cubed.

As such, the cubic filter can selectively amplify or attenuate the disturbance signal depending on the ratio u/N, to thereby attenuate the position error in the PES due to said narrow-band disturbances. By using the cubic fulter, there is variable gain on the peak filter and a resulting variable attenuation of the PES. The effect of the cubic gain function is two-fold. First, the cubing operation redistributes the energy of the input signal by creating the third harmonics at the triple of the base frequency. Second, due to cubing, the ratio of u to N (i.e., u/N) is increased or decreased if the absolute value of u/N is larger or smaller than 1, respectively.

As such, the cubic function $f(u)$ provides non-linear gain based on the magnitude of the NRRO disturbance signal, u. The parameter M adjusts the overall amplification of the value $(u/N)^3$. Therefore, if the target NRRO disturbance signal is weak, amplification by the cubic function $f(u)$ is low, and if the NRRO disturbance signal is strong, amplification by the cubic function $f(u)$ is high. Stated differently, when the NRRO signal is weak, then the output

of the non-linear gain function *f(u)* is small, and essentially does not affect the servo-loop. However, if there is a substantial level of NRRO, then there is high amplification by the non-linear gain function *f(u)*.

The output values of the non-linear gain function *f(u)*, when added to the original PES signal by the summing node 206 in the nonlinear filtering arrangement 200 of **Figure 2**, effectively adjust (vary) the attentuation level of the position error in the PES. As a result of that non-linear gain, the PES and settling performance is maintained when the disturbance signal amplitude is very small.

The non-linear gain effect of the cubic function *f(u)* is confined to a narrow frequency band due to the peak filter 202. In one example application, in disk rocking mode, the third harmonics(e.g., around 6 KHz) are significantly attenuated by the lowpass filtering nature (e.g., -40 dB/dec) of the VCM dynamics. **Figure 4** shows an example Fourier Transform (FFT) plot of the PES in a disk drive over a rocking mode frequency range, without any disturbance signal attenuation. The PES decomposition shown in **Figure 4** includes a repeatable run out (RRO) plot 212 and a NRRO disturbance signal plot 214.

Figure 5 shows an FFT plot (similar to that of **Figure 4**), wherein the disturbance signal 214 has been attenuated by the non-linear filtering arrangement 200 of **Figure 2**, over the rocking mode frequency range, according to the present invention. The non-linear filtering arrangement 200 provides selective variation of the disturbance signal 214 over the selected frequency range, and improves the overall PES when the target disturbance is present. It does so while maintaining PES performance when target disturbance is not present, and preserves settling performance regardless of the presence of a target disturbance.

The non-linear gain function $f(u)$ for automatic attenuation level adjustment depends on the disturbance magnitude. As such, in relation (1) above, the value N is selected as the threshold level of signal increase/decrease, and the value M is selected for setting the overall gain. Accordingly, the present invention provides combined usage of non-linear gain and narrow-band peak filter to confine the non-linear effect in a predetermined frequency. The disturbance signal is selectively varied (e.g., attenuated/amplified) by the non-linear function.

The frequency response of the peak filter 202 can be selected by experimentation based on the frequency range of the disturbance signal to be varied (adjusted). The spectrum shown in **Figure 5** is different from disk drive to disk drive. In one example, the base frequency is 2 KHz, and is determined by manufacturing and disk geometry such as form factor, materials, components, etc. As such, the non-linear filtering arrangement is tuned for a particular type of disk drive product. Identification of the NRRO disturbance frequency range can be determined using industry standard measurements, such as spectrum analysis software. Then, the peak filter 202 may be designed accordingly using the industry standard measurements.

Figure 6 shows an example non-linear filtering arrangement 300 according to another embodiment of the present invention. The example non-linear filter arrangement 300 includes a band pass filter 302, an optional saturation block 304, a non-linear gain function 306, an optional deadzone block 308 and a combiner node 310. The optional saturation and deadzone blocks 304, 308, respectively, can be placed in a different order than that shown in **Figure 6**.

The filter 302, the non-linear gain function 306, and the combiner node 310, operate in a similar manner as the filter 202, the non-linear gain function 204 and the combinder node 206, respectively, described above in relation to **Figure 2**. The saturation block 304 protects the servo-loop stability by controlling the output of the non-linear filter arrangement 300, which may grow very large due to the non-linear cubic gain function 306, *f(u)*. For example, the saturation block 304 may include a limiter, that limits the action of the cubic gain function 306, to maintain loop stability. The saturation block 304 imposes upper and lower bounds on the input signal. When the input signal is within the range specified by a lower limit and an upper limit, the input signal passes through unchanged. When the input signal is outside these limits, the signal is clipped to the upper or lower limits. The saturation block 304 can be implemented as ASIC, firmware, program instructions for execution by a CPU, etc.

Further, the deadzone gain block 308 eliminates the cubic effect when the target disturbance is very small. The deadzone, created by the integer division of fixed-point digital signal processing, blocks the cubic function effect

if the target disturbance is neglible, hence preserving the original PES performance intact. In one example, the deadzone block 308 defines a region of zero output. If the input of the deadzone block 308 is within a selected minimum and maximum (the zone), its output is zero. Outside of this zone, its output is a linear function of the input with a slope of 1. The deadzone block 308 can be implemented as ASIC, firmware, program instructions for execution by a CPU, etc.

Figure 7 shows an example non-linear filtering bank arrangement 400 according to another embodiment of the present invention. The arrangement 400 includes multiple non-linear filtering branches 402a, 402b of the types shown by example in **Figures 2 and 6**. In cases where the NRRO disturbance signal has multiple peaks at different frequencies, the non-linear filtering bank arrangement 400 of **Figure 7** provides attenuation of the NRRO signal at the multiple peak frequencies. The first branch 402a includes a peak filter 404, a saturation block 406, a non-linear gain function 408 and a deadzone block 410. The second branch 402b includes a peak filter 412, a deadzone block 414, a non-linear gain function 416 and a saturation block 418. The correction value outputs of the branches 402a and

402b are combined with the original PES via the combiner node 420 to generate a corrected PES with reduced disturbance signals.

Preferably, the peak filter in each branch 402a, 402b, is at a different base frequency than the other peak filter. Further each branch 402a, 402b, can have a different non-linear gain function, and different optional saturation and deadzone blocks. The branches 402a, 402b can operate in parallel, or selectively in response to control signal based on the NRRO peaks.

According to another aspect of the present invention, the example non-linear filtering arrangements above can be activated when the servo controller enters the on-track mode (i.e., after a seek operation to a target track and while tracking the target track). By careful tuning through simulation, the transient response shows virtually no difference when the cubic function $f(u)$ is operating.

As such, the present invention provides selective attenuation of the position error due to narrow-band disturbances in the PES by a non-linear gain function for automatic level adjustment of the disturbance signal in the

PES depending on the disturbance signal magnitude. This provides combined usage of nonlinear gain and narrow-band peak filtering to confine the non-linear effect for a predetermined frequency. Further, in the example non-linear gain function of relation (1) above, the value N for the threshold level of signal amplification/attenuation, and the value M for setting the overall attenuation level, are selectable based on desired performance criteria.

As will be appreciated by those skilled in the art, in addition to the logic blocks shown in the drawings, the various methods and architectures described herein can be implemented as: computer instructions for execution by a microprocessor, as ASIC units, firmware, as logic circuits, etc. For example, the above steps and functions can reside as firmware in the servo controller (to be triggered on and off), or as a logic circuit in the disk drive controller.

The present invention has been described in considerable detail with reference to certain preferred versions thereof; however, other versions are possible. For example, although a cubic odd function is used in this embodiment, other odd functions such as a 5^{th} order odd function can also be used. Therefore, the spirit and scope

of the appended claims should not be limited to the description of the preferred versions contained herein.